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DEVELOPMENT OF DISTRIBUTED COMPLIANT MECHANISM FOR DISPLACEMENT AMPLIFICATION

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ABSTRACT

In the present paper, a distributed compliant mechanism capable of performing specified mechanical function of Geometric Amplification (GA) is presented. The geometry of the mechanism is developed considering a predefined design domain (size constraint) to achieve a GA of two (2) using the principles of topology optimization. The proposed distributed compliant mechanism is modeled and analyzed in order to obtain the desired GA by considering two different materials i.e. Al and Stainless Steel. The nonmetallic prototype of the distributed compliant mechanism was manufactured by using rapid prototype technique to visualize performance. Further, metallic distributed compliant mechanism using aluminum and stainless steel were manufactured using laser cutting technique. The performance of mechanism was ascertained with the assistance of an experimental setup. The results of experimentation and simulated were observed and are in convergence.

KEYWORDS: Compliant Mechanism, Geometric Amplification (GA) & Topology Optimization

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Original Article

INTRODUCTION

Compact micro-motion devices are preferred to deliver high position in g accuracy and potentially have a wide range of applications in industry. Compliant mechanisms are jointless mechanical devices used to transform displacement, force, or energy from one point to another. A compliant mechanism achieves flexibility due to elastic deformation. Lumped compliant mechanisms are commonly used, however distributed compliant mechanisms are necessary due to its compactness and advantages. Lumped mechanisms have motion at flexure hinge but in case of distributed mechanisms deformation is observed in the entire mechanism which can avoid localized stress concentration. Topology optimization is a mathematical method that optimizes material layout within a given design space for a given set of loads, boundary conditions and constraints with the goal of maximizing the performance of the system [1]. A distributed compliant mechanism capable of gripping objects has been proposed in current work. Compliant mechanisms with distributed compliance for maximizing GA have been considered as design approach for improved reliability, performance, and ease of manufacturing (joint less) [2]. In case of manipulation of micro objects high precision in motion is required. A three fingered micro gripper for precise manipulation is attained based on the appropriate mechanism design of micro devices [3]. The concept of hinge-free compliant mechanism has been introduced with an objective function to maximize the GA [4]. Topology optimization is also achieved using a level set method. Hinge-free micro gripper and inverter mechanism have been developed using level set method of optimization [5]. The evolutionary structural optimization procedure is also applicable in topology optimization of compliant mechanisms in ceitis convenient to modify traditional way of

material removing techniques [6]. A general topology optimization method for compliant mechanism synthesis of statically loaded structures viz. gripper and inverter are proposed wherein only 50% of the design domain is considered while designing the mechanism [7]. A multi-objective technique of structural topology optimization for distributed compliant mechanisms viz. micro-actuators used in MEMS application is presented, with an objective to provide both mechanical flexibility and structural stiffness along with density filtering approach [8]. Structural optimization method using mathematical programming such as Method of Moving Asymptotes (MMA) for the design of compliant mechanism is implemented based on level set method for maximizing the GA. The grey scale areas are eliminated by using level set method [9]. A monolithic design of micro grasping device is presented by implementing the topological optimization technique [10]. Further, attempts have been reported to achieve hinge-free compliant mechanism by performing parametric changes as few of mechanisms are hybrid (i.e. distributed mechanisms with 1 or 2 flexure hinges). A compliant micro gripper is formed by using ground structure parametrization of the optimal topology [11]. Luzhong Yin had proposed a mathematical model for topology optimization for distributed compliant mechanisms. The model proposed is generic and has been customized in tune with the specific mechanical function of geometric amplification in current work. The mathematical model has proved to be effective while deciding the topology [12].

DEVELOPMENT OF DISTRIBUTED COMPLIANT MECHANISM

Functionality of Mechanism

An object holding capable of holding objects and moving them from one place to another mechanism is selected in current study. Depending on the size of the object, the mechanism should be capable of resulting into increased travel for small sized objects. This mechanism will use amplified displacement of its holding end to grab objects.

Design Domain and Boundary Condition

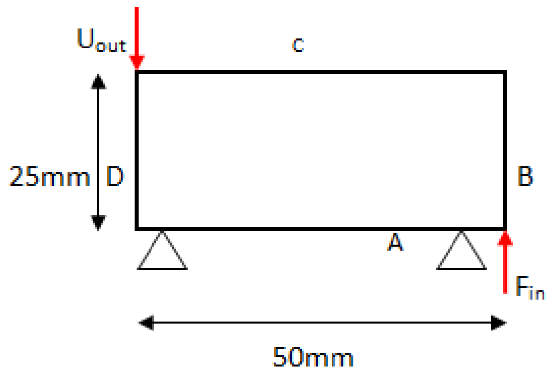

Figure 1: Design Consideration.

Here, the main goal of optimization is to maximize the output displacement in a desired direction. Consider the Figure 1 where the displacement is at boundary ‘D’ when an input force Fin is applied at diagonally opposite boundary ‘B’ and Uout is displaced along the desired output direction. To achieve above mentioned target, first task is to select appropriate dimensions for the Design Domain.

Topology Optimization

The mechanism should ensure sufficient flexibility and stiffness for deformation along the direction of input force. By maximizing the mutual strain energy, the output displacement is maximized along the desired direction. In order to attain a

hinge free mechanism, a volume constraint of 30% of the design domain volume is considered. By minimizing the total strain energy, structural stiffness can be maximized. Thus, objective function of the topology optimization problem can be described as:

Objective function: $$\text{Max}\,\frac{MSE}{SE}\ \text{or Min} -\frac{u^T KU}{\frac{1}{2}U^T KU} \quad (1)$$

Subject to: $$V^T\rho - V^* \leq 0 \quad (a)$$

$$KU = F \quad (b)$$

$$Ku = f \quad (c)$$

Where,

MSE – Mutual strain energy

SE- Strain energy

u – Unit virtual displacement vector

U – Displacement vector due to force F

f – Internal force due to unit virtual load

F – Externally applied force

K – Stiffness of element

V- Total volume

V* **-** Upper bound on volume

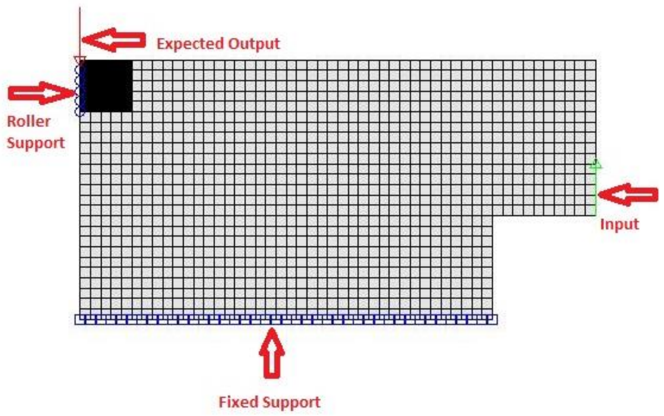

Figure 2: Design Domain.

Figure 2 represents the design domain, a void region at bottom right corner of 10 mm x 10 mm is provided to accommodate actuator to give input displacement/ force. A solid region of 5mm x 5 mm is also provided diagonally opposite of void region just below the place where the output is expected so as to ensure dense material for holding the

object.

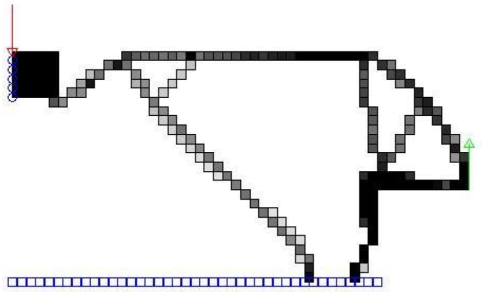

Figure 3: Optimized Geometry.

Design domain is discretized in element size of 1 mm x 1mm. As shown in figure 1, edge A of design domain is fixed and the solid region along part C is roller supported to restrict the output displacement in Y direction only.

The bottom part of optimized geometry is not subjected to any force and so only some part is useful for mechanism, as shown in Figure 3.

MODELING AND ANALYSIS OF PROPOSED GEOMETRY

The optimized geometry is stepped and not continuous and it will be difficult to manufacture an object with such geometry, hence smoothening is required at corners also localized stress concentration can be observed.

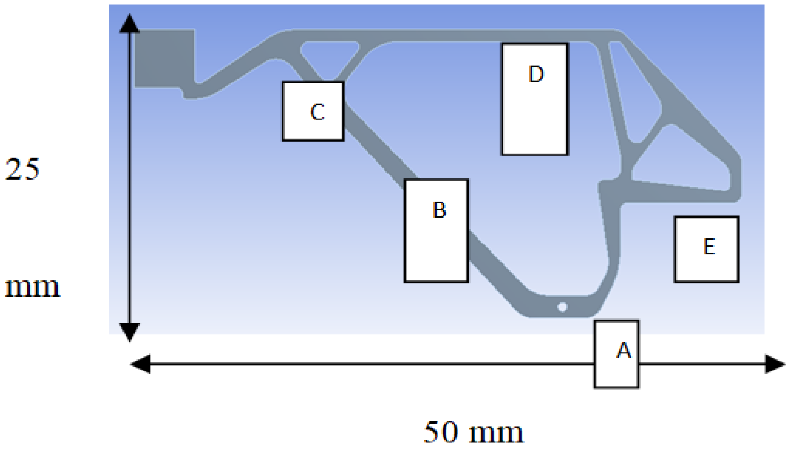

Figure 4: Modeling of Optimized Geometry.

The model is analyzed for an input force of 10N and mechanism is fixed using a hole in the link A for Aluminum material, as shown in figure 4.

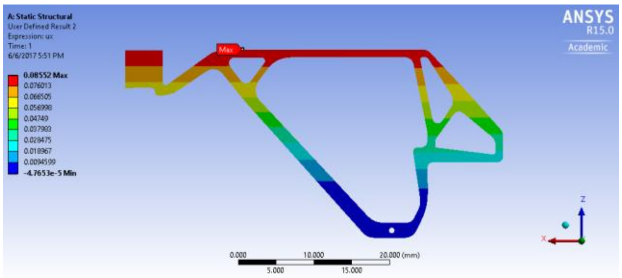

Figure 5: Total Deformation.

The maximum equivalent stress occurred is 76.60 MPa and output displacement is 3.07 times the input displacement with the volume fraction of 0.165.

DESIGN FOR MANUFACTURING

Modifications in geometry are undertaken in order to manufacture the geometry without compromising with GA of mechanism, as it will be difficult to manufacture the mechanism with no linkage to fix the mechanism for experimental evaluation.

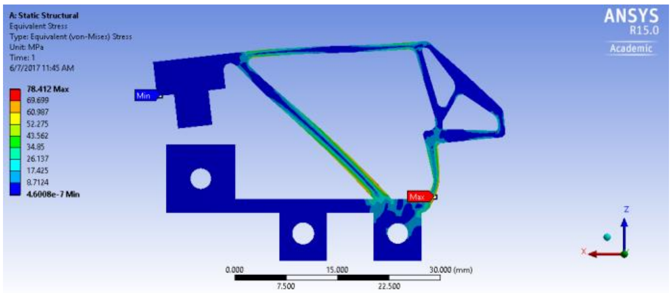

Figure 6: Total Deformation of Modified Geometry.

The modified model is prepared by considering clamping positions of the mechanism and jaws for holding the object. The comparative FEA results of modified geometry and initial geometry are represented in Table 1. It can be observed that volume fraction of the modified geometry is increased due to increase in overall material of the mechanism out of design domain.

Table 1: Comparison of Results of FEA Analysis

Parameters	Proposed Geometry	Modified Geometry
Maximum Stress (MPa)	76.60	78.41
Geometric Advantage (GA)	3.07	2.745
Displacement in X-dir (mm)	0.0855	0.1027
Volume fraction (Vf)	0.1655	0.3665

The mechanism is checked for its performance under different load conditions in order to estimate its strength. The load is applied from 2 to 20 N. The stress level at 20 N is obtained as 174.45 MPa for Stainless steel and 156.81 MPa for Aluminum which is well within the permissible limits of both the materials.

MANUFACTURING OF COMPLIANT MECHANISM

Manufacturing methods should be selected such that it will generate complex shapes without introducing residual stresses and this can be easily achieved by using laser cutting technique. Mechanism is manufactured using stainless steel and Aluminum material for experimentations. But before going for experimentation, the mechanism needs to be visualized about its working. Therefore, before manufacturing on laser cutting prototype of mechanism is printed on 3D printer using ABS plastic as shown in Figure 7.

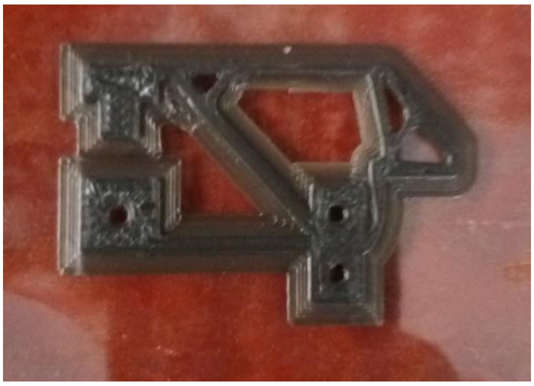

Figure 7: 3D Printed Compliant Mechanism.

The desirable performance was observed from 3D printed model and so metallic mechanisms have been manufactured for experimentations using laser cutting technique. The two point extension to fix the mechanism with base plate is used to avoid curvilinear path of mechanism as it can be detected for single point extension.

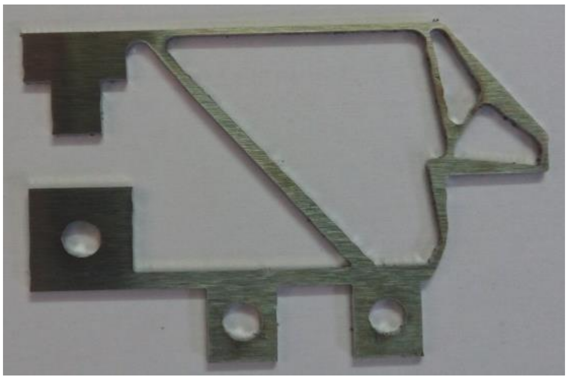

Figure 8: Laser cut Compliant Mechanism.

EXPERIMENTAL EVALUATION

The object holding compliant mechanism is mounted on a grounded metal plate for ease of experimental trials and small holes are made to place steelballs and so make point contact with metal plate and fixed using screws as shown in Figure 9 and a miniature precision micro slide is used to provide input displacement (least count 0.01 mm).

The prepared setup is tested for a certain range of displacements. The obtained results from experimentation are compared with the FEA results. Figure 9 shows the experimental trials performed using optical 3D Profilometer. 3D Profilometer is able to measure micro scaled reading with greater magnification.

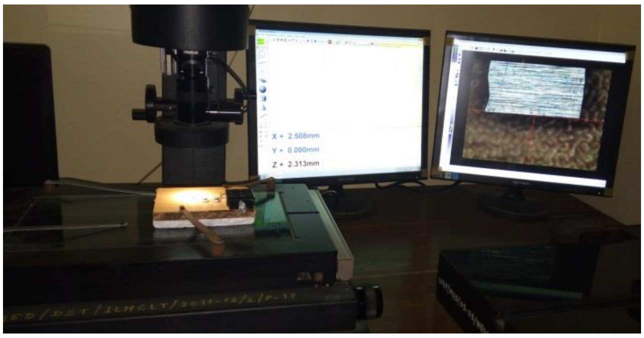

Figure 9: Experimentation on 3D.

RESULTS AND DISCUSSIONS

Correlation between the force (N) and Displacement (mm) is represented in figure 10. From the trend, it is also observed that relationship between Force and output displacement is linear in nature. This graph can be used to predict the output displacement at any intermediate force value.

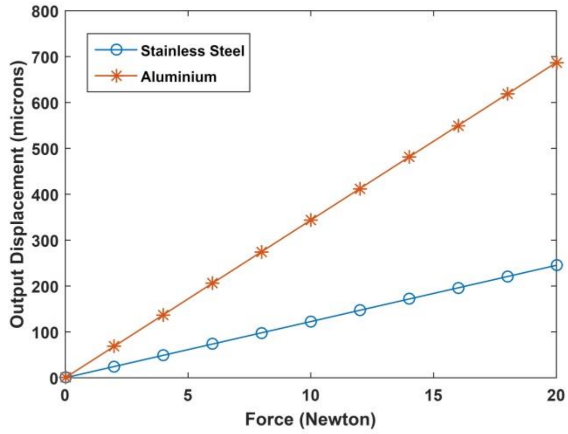

Figure 10: Input Force vs Output Displacement Result of SS and Al

The comparative study between FEA and experimental results is carried out for Al and for Stainless Steel material as shown in Figure 11.

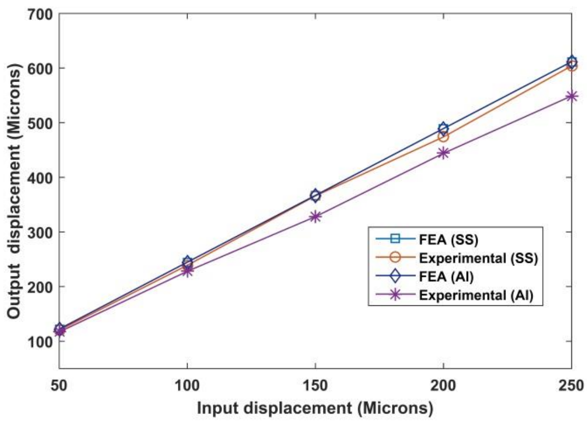

Figure 11: Comparison of FEA and Experimental of SS and Al.

It is observed that object holding compliant mechanism manufactured using Al material is able to amplify the input displacement by 2.1 to 2.5 times and Stainless steel is amplifying the input displacement by 2.35 to 2.45 times.

In this case, all the experimental results are close to numerical results. Percentage error for all the experimental output displacement is within 5%.

CONCLUSIONS

In current work, a distributed compliant mechanism capable of performing specified mechanical function of Geometric Amplification (GA) is presented. By using the principles of topology optimization, the geometry of the mechanism can be developed considering a predefined design domain. As the experimental trials were observed for micro scale readings,

highly accurate experimental setup is required to verify FEA results. By comparing both materials, it can be concluded that for specific force values Aluminum material gives higher output displacement than Stainless steel material with lower maximum stress value, which is 36%. The FEA results show that designed compliant holding mechanism is able to sustain load up to 20N without fail.

REFERENCES

1. *Larry L Howell 2001 CompliantMechanism, A Wiley-Interscience Publication, New York.*
2. *Sridhar Kota, JinyongJoo, Zhe Li, Steven M. Rodgers and Jeff Sniegowski 2001 Design of CompliantMechanisms: Applications to MEMS, AnalogIntegrated Circuits and Signal Processing, 29, 7–15.*
3. *R. Bharanidaran and B. T. Ramesh 2013 Design of CompliantMechanismBasedMicrogripperwithThreeFingerUsingTopologyOptimization, International Journal of Mechanical, Aerospace, Industrial, Mechatronic and Manufacturing Engineering 7, No: 7, 1385-1390*
4. *Y. Li, X.Huang, Y.M.Xie, S.W.Zhou 2014 Evolutionarytopologyoptimization of hinge-free compliantmechanisms, International Journal of Mechanical Sciences 86, 69–75.*
5. *JunzhaoLuo, ZhenLuo, Shikui Chen, Liyong Ton and Michael Yu Wang 2008, A new level set method for systematic design of hinge-free compliantmechanisms, Comput. MethodsAppl. Mech. Engrg. 198, 318–331*
6. *" Design and Optimal Synthesis of Compliant Mechanisms – An Optimality Criteria Approach ", IJMPERD, Vol. 8, Issue 1, pp.1309-1316*
7. *Ruben Ansol, EstrellaVeguería, Javier Canales, Jose A. Tarrago 2007 Asimpleevolutionarytopologyoptimizationprocedure for compliantmechanism design", FiniteElements in Analysis and Design 44, 53 – 62*
8. *Anderson Pereiraa, Ivan F. M. Menezesa, Cameron Talischib and Glaucio H. Paulino, 2011 An Efficient and Compact MatlabImplementation of TopologyOptimization: Application to CompliantMechanism, XXXII Iberian Latin-American Congress on ComputationalMethods in Engineering*
9. *" Design of Compliant Mechanisms for New Age Industry Devices –A Topology Optimisation Approach ", IJMPERD, Vol. 7, Issue 6, pp. 653-662*
10. *LuoZhen, Du Yixian, Chen Liping, Yang Jingzhou and Karim Abdel-Malek, 2006 Continuum topologyoptimization For MonolithicCompliantMechanisms Of Micro-Actuators, Acta MechanicaSolidaSinica, Vol. 19, No. 1, 58-68*
11. *M. Otomori, T. Yamada, K. Izui, and S. Nishiwaki 2011 Level set-basedtopology optimisation of a compliantmechanism design usingmathematicalprogramming, Mech. Sci., 2 91–98*
12. *" Influence of Pretwisting angle on the Buckling Capacity of Steel Columns: A Review ", International Journal of Civil Engineering (IJCE), Vol. 5, Issue 6, pp. 1-10*
13. *Bharanidaran.R and Ramesh.T 2016 Topological Design and Analysis of Micro GraspingDevice, International Journal of Research in AdventTechnology, Vol.4, No.9, 73-76*
14. *Shyh-Chour HUANG, Chi-Ming LEE, Chien-Ching CHIU and Wei-Liang CHEN 2006 Topology Optimal CompliantMicrogripper, JSME International Journal, Series A, Vol.49, No. 4, 589-596*
15. *" Seismic Response Control of a Cantilevered Highway Sign Support using a TMD ", International Journal of Civil Engineering (IJCE), Vol. 6, Issue 6, pp. 51 - 60*
16. *Luzhong Yin, G. K. Ananthasuresh, 2016 As a part of postdoctoral work, ME 256 VariationalMethods in Mechanics and*

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